
Weatherwise

ISSN: 0043-1672 (Print) 1940-1310 (Online) Journal homepage: http://www.tandfonline.com/loi/vwws20

# Frost Quakes: Forecasting the Unanticipated Clatter

**Steven M. Battaglia & David Changnon**

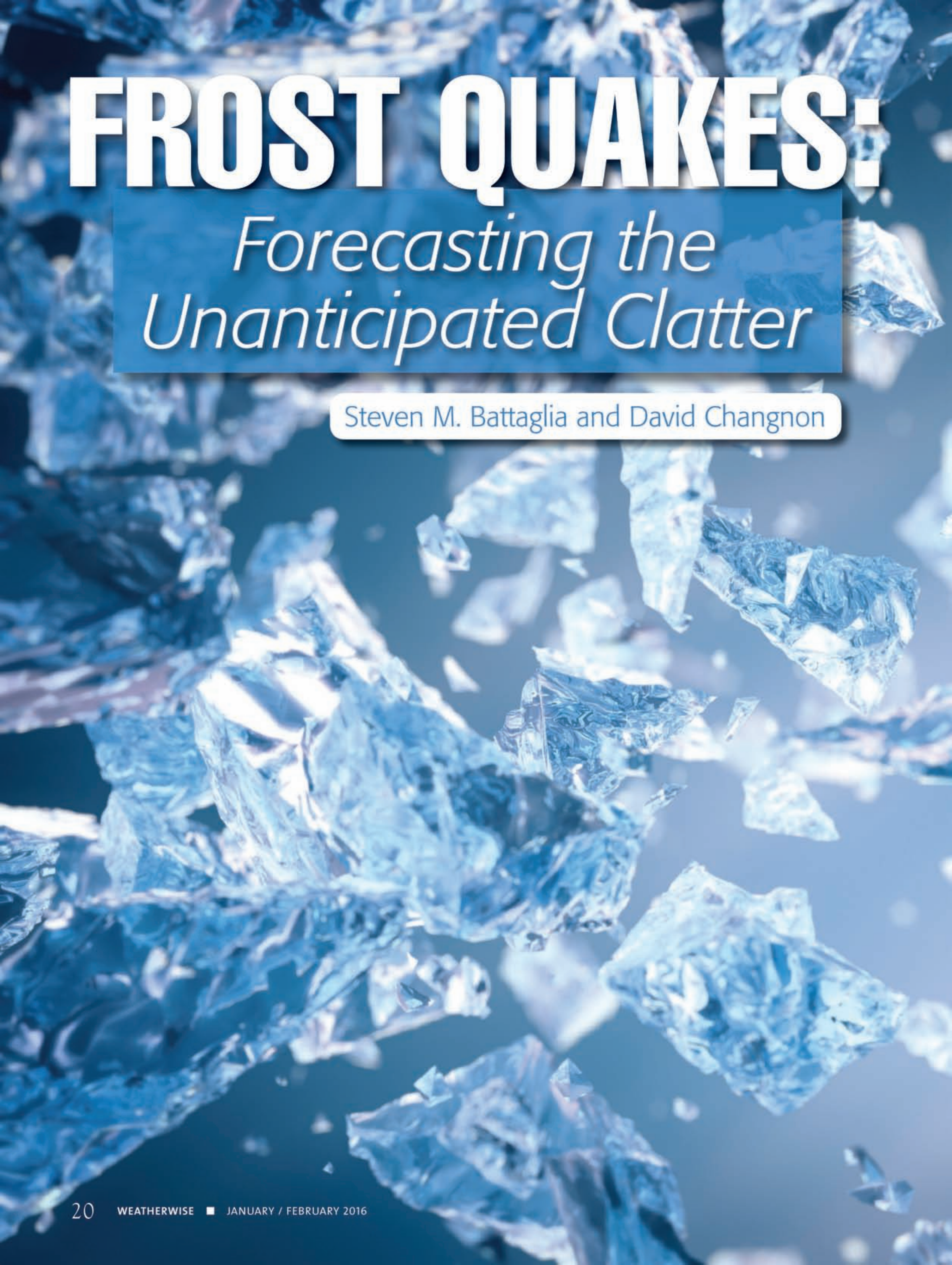
**To cite this article:** Steven M. Battaglia & David Changnon (2016) Frost Quakes: Forecasting the Unanticipated Clatter, Weatherwise, 69:1, 20-27

**To link to this article:** http://dx.doi.org/10.1080/00431672.2015.1109984

Published online: 15 Dec 2016.

# FROST QUAKES:
## *Forecasting the Unanticipated Clatter*

Steven M. Battaglia and David Changnon



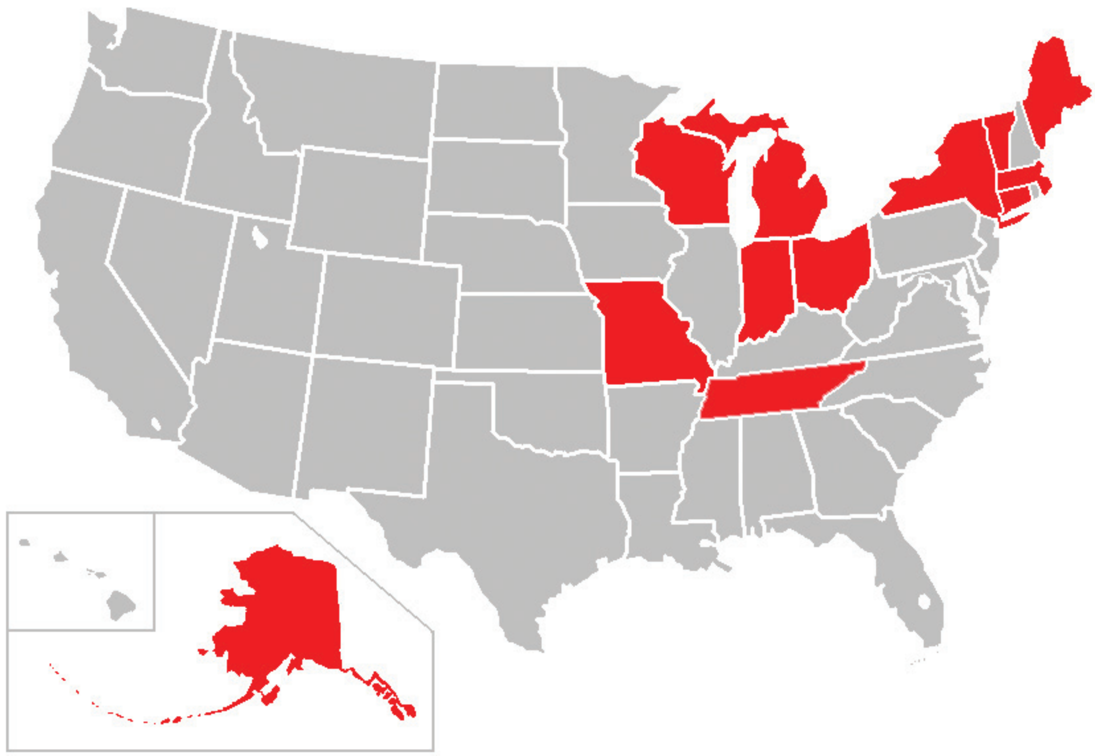

ISTOCK/SHAUNI

ISTOCK/SKEGBYDAVE

Numerous frost quake reports, especially those recorded during the 2013–2014 winter season, occurred during one of several arctic air outbreaks that impacted the eastern two-thirds of North America in recent years.

A Toronto, Canada, neighborhood blanketed by a few inches of snow glistens beneath the moonlight on a mid-January, winter night. The temperature outside is slightly above freezing as a weather system passes through southern Ontario, dragging with it a significant cold air mass and a temperature that plummets to subzero within 24 hours. As the frigid air converges on the neighborhood, a loud, explosive noise rattles a few homes in the middle of the night. Social media and police stations are flooded with numerous unidentified reports, which include talk of ruptured pipes, gunfire, and bright flashes of light in the vicinity of the blast. The extreme burst of pressure released at the earth's surface was the unexpected roar of a frost quake.

WIKIMEDIA COMMONS/SPLOT



States with reported cryoseisms.

## Winter's Fury

The intriguing phenomenon of rambunctious, violent blasts that has been reported during the past two winters (2013–2014, 2014–2015) is interpreted to be *cryoseisms*, or *frost quakes*. Frost quakes form during the wintertime (in the Northern Hemisphere) when the surface temperature undergoes a rapid cooling from above freezing to near subzero (degrees Fahrenheit). The water that saturates the ground directly beneath the surface solidifies from below-freezing temperatures. The subsurface ice continues to expand as the temperature cools because water molecules, upon cooling, arrange themselves into a structure that takes up more volume than when the molecules were arranged in a liquid. This continuous expansion imposes a large amount of stress on the local surrounding frozen soil and rock around the ice. The surrounding frozen surface can withstand the increase in pressure from the expansion of ice for a while, but not for as long at very low temperatures and high pressures. Once the pressure is too great, it is relieved violently—a fracture on the surface forms and a loud, explosive noise echoes within the proximity of the breakage! This earsplitting, fast-action fracture and clamor is a frost quake.

Southern Ontario province in Canada held the most reports of frost quakes during the winter of 2013–2014, with many of them occurring near Toronto and the surrounding area. A few isolated frost quake reports also came out of the United States Midwest in states such as Wisconsin, Missouri, Indiana, and Ohio. During the winter of 2014–2015, reported frost quake occurrences were in southern Ontario and Quebec or near Montreal, Ottawa, and Toronto, and a few cities in the United States including Kansas City, Missouri, and Jackson, Tennessee.

The numerous frost quake reports, especially those recorded during the 2013–2014 winter season, occurred during one of several Arctic air outbreaks that impacted the eastern two-thirds of North America. One of the strongest cold snaps was recorded on January 6–7, 2014. Dozens of record lows were set across the contiguous United States and southeastern Canadian provinces after a strong nor'easter that brought bitterly cold temperatures and, in some locations, heavy snow.

## Frost Quakes: A History

The first documented frost quake occurrence was published in 1819. Edward Hitchcock, an American geologist, reported a singular disruption (one large surface crack) on the ground in Deerfield, Massachusetts, to the *American Journal of Science*. In his letter to the journal editor, Hitchcock wrote: "… About one o'clock in the morning of March 4th, Mr. Seth Sheldon and family, living one mile south of this spot, and being awake, were alarmed by a loud report

from the north, by which their house and furniture were much shaken. Some others living rather near the spot, were awakened by the same report…." Hitchcock concluded that the ground disruption was likely caused by ruptured frost on the surface that resulted from a nearby river flooding a few days prior to an intruding cold air mass.

In 1980, Andrew V. Lacroix of the Western Geophysical Corporation in Westboro, Massachusetts, published a short note on frost quakes in the journal *Earthquake Notes*. Lacroix compiled frost quake reports from previous literature to discriminate between earthquakes that were caused by the freezing action of ice and those caused by tectonics. He discovered that the majority of published and unpublished frost quake reports since Hitchcock's letter of Deerfield's ground disruption were reported in the northeastern states (such as Maine, Massachusetts, New York, and Vermont) and southeastern region of Canada (southern Ontario and Quebec), but that frost quakes were likely not unique to solely these regions.

From his report compilation, Lacroix characterized frost quake occurrences into three categories: (i) seismological characteristics, (ii) geological conditions, and (iii) meteorological conditions. Frost quake seismic events were often not intense enough to be detected at seismic stations and therefore only sufficient booming, cracking, or thundering noises were reported by adjacent persons and restricted to a *felt*, or nearby, area. The only geological information provided of the reported areas was that the surface was typically made of permeable materials with susceptibility to frost action (such as gravels and sands).

## The Meteorology Behind Frost Quakes

Although geologists, and geology-related themes, have been the dominant source for documenting the manifestations of frost quakes, Lacroix has shed light on the importance of the meteorological aspects, and atmospheric parameters, of this naturally occurring anomaly. The meteorological conditions consisted of four basic characterizations:

1. Perennial or seasonal frost conditions
2. Rapid saturation produced by thaw, rain, or flooding
3. Little or no snow cover on the ground
4. Rapid rate of change of sub-freezing temperature

Why did southeastern Canada and parts of the northeastern and midwestern United States have more frost quakes in the previous two winters than typical cold seasons? Southern Ontario and the Quebec provinces, and much of the northern states, are susceptible to annual frost during Northern Hemispheric wintertime. The other meteorological variables that played a significant role in the frost quake events were temperature, snow depth (the average depth of snow, including old snow and ice, on the ground at the time of an occurrence), and momentous cold outbreaks of Arctic air, following the characteristics put forth by Lacroix (Figure 1).

In the subsequent sections, we review five frost quake events from southeastern Canada, followed by similar reports from the United States, in the 2013–2014 and 2014–2015 winter seasons. We focus on the atmospheric parameters that are imperative to make a forecast of a future frost quake outbreak.

## Reports in Canada

### December 24–25, 2013

Reports of loud booms in Toronto surfaced during the overnight hours from the evening of December 24 to the morning of December 25. The recorded high temperature in the city was

WIKIMEDIA COMMONS

Portrait of Edward Hitchcock, who wrote the report on the first documented frost quake in 1819.

35°F on December 23. The snow depth was roughly one inch. Atmospheric conditions on December 23 and 24 included light snow to clear skies. From December 23–25, about a 48-hour period, the temperature plummeted roughly 30 degrees, resulting in a low of 5°F.

Ottawa and Montreal did not have any reported frost quakes from December 24–25. On December 23, the recorded high temperatures in these cities were 20°F and 22°F, respectively. The snow depth was between 12 and 16 inches, and the weather was variable with snow and cloudy to clear skies. The low temperatures recorded on December 25 were –12°F in Ottawa and –4°F in Montreal.

### December 29, 2013–January 3, 2014

Some reports of explosion-like noises emerged on January 2 and in the early morning hours of January 3 from the Toronto area. The recorded high temperature in the city was 39°F on December 29, four days prior to the frost quake event and the last day before the temperature dropped below freezing. The snow depth was about one inch, similar to the depth observed December 24–25 in Toronto. The weather was variable with cloudy skies and light snow around the New Year. From December 29 to the morning of January 3, the daily low temperature gradually descended a total of 46 degrees to –7°F.

Ottawa and Montreal did not have any reported frost quakes. The recorded high temperature for Ottawa on December 29 was 33°F, while Montreal remained below freezing. The snow depth was between 10 and 11 inches. Following the temperature drop, the recorded low for Ottawa was –2°F overnight on December 30.

### January 6–7, 2014

Likely the biggest frost quake event on record occurred when numerous reports of loud booming and thundering noises in the Toronto area came in the evening of January 6 and the morning of January 7. The recorded high temperature in Toronto on January 6 was 34°F (Figure 2). The snow depth was roughly two to four inches. Early snow showers turned to clear skies on January 6 prior to the temperature decline. During the morning of January 7, the recorded low temperature was –7°F, indicating a rapid change of temperature in approximately 24–28 hours.

A few reports of frost quakes came out of Ottawa and Montreal, the first events of their winter seasons. The high temperatures in both cities on January 6 were 42°F and 43°F, respectively. The snow depth had decreased from the previous two events to six to eight inches in Ottawa and 10 inches in Montreal. The recorded low temperature from the intruding arctic air was 0°F the morning of January 7.

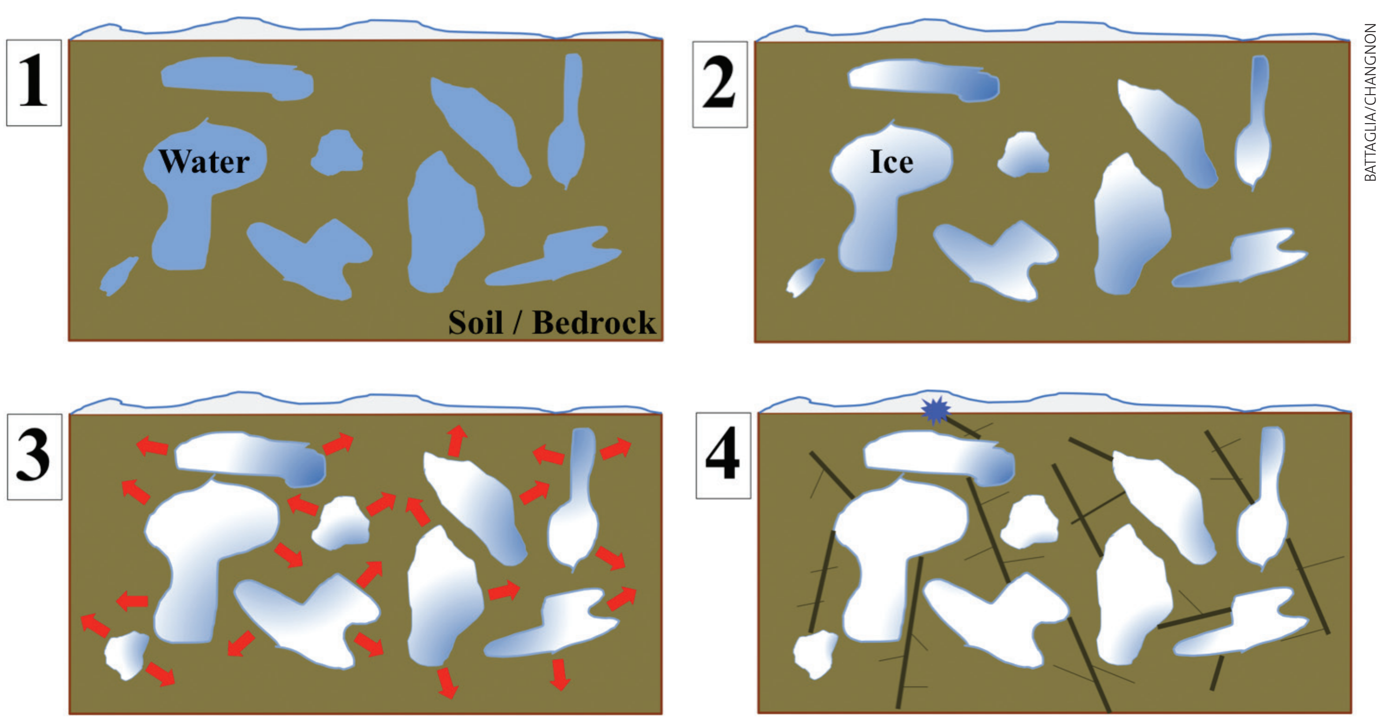



Figure 1. The general process for a frost quake formation. Panel [1]: Water saturates the soil or bedrock near the surface from thaw, precipitation, or flooding and is essentially "trapped" in the ground. Panel [2]: As the surface temperature cools, the water in the subsurface freezes. Panel [3]: The ice begins to expand as the temperature continues to cool (as shown by red arrows) and increases the pressure on the surrounding soil/bedrock. Panel [4]: The stress from the expansion of ice is too much and causes fractures to form that can create a loud noise and, occasionally, ground shaking.

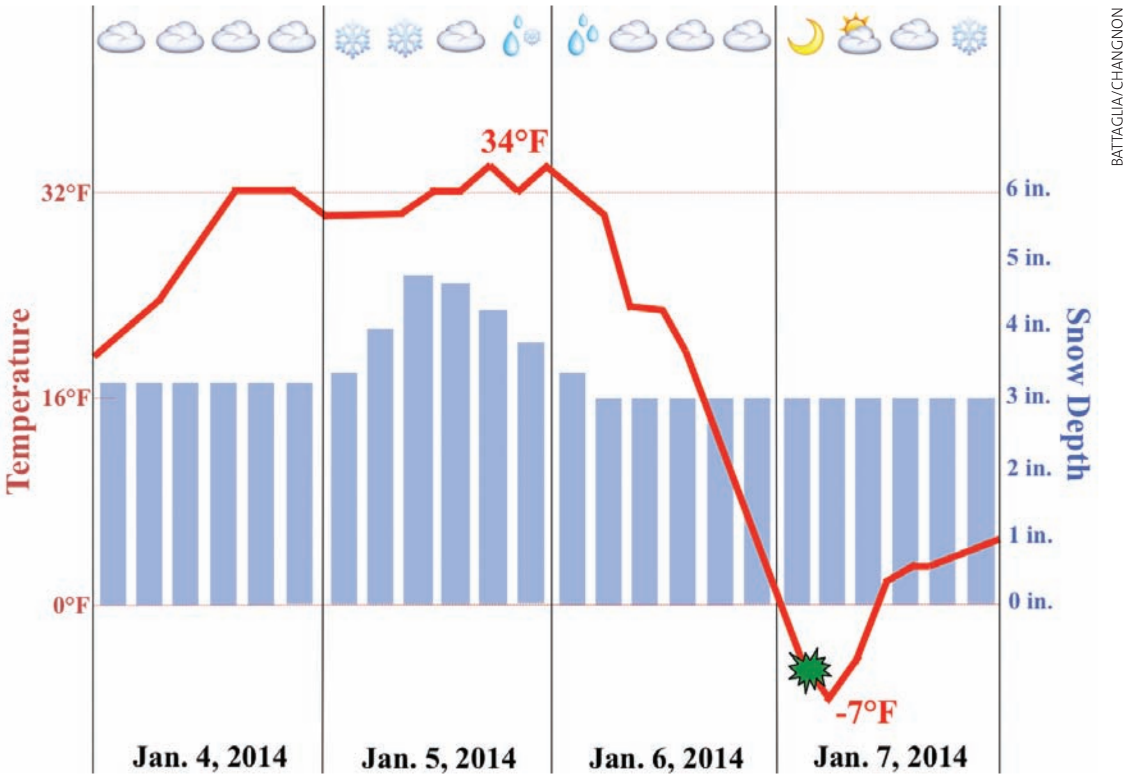



Figure 2. Temperature (red line graph), snow depth (blue bar graph), weather conditions (top symbols), and frost quake occurrences (green symbol) in Toronto, Ontario from Jan. 4–7, 2014.

### January 5–6, 2015

Ottawa and Montreal recorded a large number of frost quakes in both cities, making this the first significant event of their 2014–2015 winter seasons. The recorded high temperatures on January 4 were 31°F and 38°F in Ottawa and Montreal, respectively (Figure 3). The snow depth was about six inches for Ottawa and between two and three inches for Montreal. The weather in both cities included a wintry mix of freezing rain and snow on January 4 and cloudy to clear skies on January 5. From January 4 to the morning of January 6, the temperature plummeted 40 degrees to –10°F (Ottawa) and –4°F (Montreal).

Only a few frost quake reports surfaced from Toronto compared to the numerous amounts from Ottawa and Montreal. On January 4, the recorded high was 41°F in Toronto. The snow depth was trace to near one inch. The weather from January 4–5 included a rain and snow mix with cloudy skies. The temperature dipped roughly 30 degrees to 10°F the morning of January 6.

### January 12–13, 2015

A few frost quake reports were noted from Toronto. The recorded high temperature on January 12 in Toronto was 32°F, right around freezing. The snow depth was around one inch. The weather included blowing snow and cloudy skies. The temperature plunged in a short period of 16–18 hours to a low of –1°F the morning of January 13. This was the most rapid change in temperature over a period of time from the six Canadian events discussed in this article.

Ottawa reported only a few frost quakes in the near vicinity of the city. Montreal did not report any frost quakes. The high in Ottawa on January 12 was 27°F. The snow depth was roughly nine to 10 inches. The weather was similar to Toronto—blowing snow and cloudy. The low temperature recorded the morning of January 13 in Ottawa was –12°F. Montreal began with a high of 28°F, which fell to a low of –8°F with a snow depth of three to four inches.

## Reports in the United States

Frost quake reports and weather conditions from the United States are similar to those reported from southeastern Canada. Below is a select few frost quake reports from the United States.

### 2013–2014 Winter Season

Frost quakes were reported in southwestern and central Ohio, near Cincinnati and Columbus, in mid-January. Temperatures went from above freezing to –4°F in less than 36 hours with a snow depth between two to five inches. In Saint Francois County, Missouri, in early

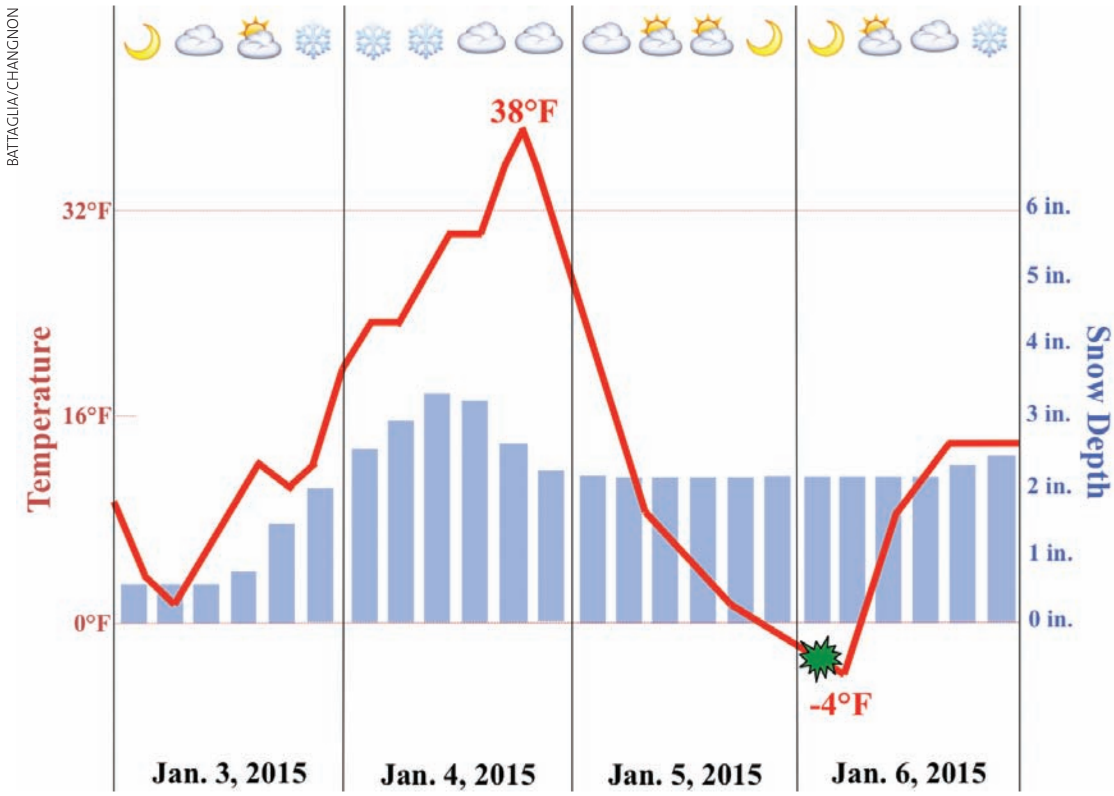



Figure 3. Temperature (red line graph), snow depth (blue bar graph), weather conditions (top symbols), and frost quake occurrence (green symbol) in Montreal, Ontario from Jan. 3–6, 2015.

February, temperatures went from the high 30s to a low of 5°F within a two-day period with a snow depth of less than two inches. About a week later near Evansville, Indiana, the temperature went from near 33°F to 4°F with a snow depth of less than four inches.

### 2014–2015 Winter Season

In Kansas City, Missouri, from mid-January to early February, reports of mysterious booms that may have been frost quakes occurred from a few cold snaps and local temperature fluctuations. On February 4–5, the temperature of 34°F dropped to a low of about –2°F in one day with one to three inches of snow depth. On February 18, near the city of Jackson, Tennessee, a couple of loud booms were reported. The temperature was at 32°F and dropped to a low of 6°F in 24 hours with a snow depth of three inches. See Table 1 for a select list of frost quake events from Canada and the United States.

## How Can We Forecast Frost Quakes?

Frost quakes do not pose a threat to humans. Public awareness of this atmosphere–surface interactive event may help to reduce the possible anxiety caused from the mystery behind why an extremely loud bang was heard in the middle of an extremely cold night!

Can the location of frost quake outbreaks be forecasted given the meteorological characteristics of their formations?

There are many variables that play a role in setting the stage for this circumstance. The geological characteristics of frost quakes are currently limited to the understanding that some sort of permeable material undergoes frost activity during the winter season. These events are typically heard in localized areas and are not generally widespread, but both urban and rural areas are prone to frost quakes. The case studies provided here increase our knowledge of the meteorological characteristics from Lacroix that aid with determining the atmospheric precursors for frost quakes.

### 1. Seasonal Frost and Susceptibility to Arctic Air Masses

It remains clear that the majority of affected areas of frost quakes have seasonal frost conditions. The ideal timing for frost quakes seems to be when there is a surplus of soil moisture recharge (in the Northern Hemispheric winter) from December through March. This includes much of Canada and the United States Midwest and Northeast. The frost quake reports from the more southerly areas of the United States Midwest can have daily temperatures above freezing and nighttime temperatures below freez-

**Table 1. Frost Quake Events from Canada and the United States.**

| Selected Frost Quake Reported Dates | City Location(s) Reporting (ON: Ontario) (PQ: Province of Quebec) | High (°F) (before cold snap) | Low (°F) (after cold snap) | Temperature Change (ΔT = High – Low) | Approx. Time Change from High to Low (hours) | Approx. Snow depth (inches) |
|---|---|---|---|---|---|---|
| Dec. 24–25, 2013 | Toronto, ON | 35 | 5 | 30 | 48 | ~1 |
| Jan. 2–3, 2014 | Toronto, ON | 39 | (-7) | 46 | 96 | ~1 |
| Jan. 6–7, 2014 | Toronto, ON | 34 | (-7) | 41 | 28 | ~2 – 4 |
| Jan. 20–22, 2014 | Cincinnati, OH | 33 | (-4) | 37 | 36 | ~2 – 5 |
| Feb. 2–3, 2014 | St. Francois County, MO | 37 | 5 | 32 | 48 | ~1 – 2 |
| Feb. 6–7, 2014 | Evansville, IN | 33 | 4 | 29 | 44 | ~2 – 4 |
| Jan. 5–6, 2015 | Ottawa, ON / Montreal, PQ | 31 – 38 | (-10) – (-4) | 41 – 42 | 30 – 38 | ~2 – 6 |
| Jan. 12–13, 2015 | Toronto, ON | 32 | (-1) | 33 | 16 | ~1 |
| Feb. 4–5, 2015 | Kansas City, MO | 34 | (-2) | 36 | 24 | ~1 – 3 |
| Feb. 18–19, 2015 | Jackson, TN | 32 | 6 | 26 | 24 | ~3 |

Frost quake reported dates in select cities with the high temperature before the cold snap, low temperature after the cold snap, the temperature and time change between the high and low, and the approximate snow depth at the time of frost quake occurrences.

ing. These locations are still susceptible to Arctic air mass outbreaks that can drastically change the temperature from above freezing to near subzero. In general, these regions are susceptible to (i) frost conditions, whether that be all day or during the evening hours, and (ii) Arctic air intrusions during the wintertime.

### 2. Saturation of Ground from Thaw or Liquid Precipitation

In the case studies provided, the ground underwent some kind of thaw or saturation event prior to the extreme temperature plummet associated with the arrival of a cold air mass. The thaw or saturation of the ground can be caused by a number of different situations: (i) air temperatures may rise above freezing, (ii) soil temperatures may increase from surface heating (i.e., sunny conditions) that can melt surface snow and could percolate into the subsurface, (iii) any liquid precipitation or wintry mix can saturate a non-frozen ground, (iv) salted streets lower the freezing temperature of ice near these roadways that may contribute to the saturation of liquid water even if the temperature does not reach above freezing, and (v) flooding from nearby lakes or rivers could also provide a means of liquid water into the ground. The saturation of the ground is, more likely than not, to occur during the daytime.

### 3. Snow Depth—Just the Right Amount

There seemed to be a consistency with snow depth in the case studies. Nearly all of the locations with frost quakes had at least some amount of snow, not too much or too little, on the ground prior to the event. The snow depth was between one and six inches for the cases with numerous frost quakes. This snow depth is likely a combined result of previous precipitation events and melted snow that saturated the subsurface from a recent warming prior to the cold air mass. Areas that had too much snow (typically greater than six inches) were less likely to have frost quakes as a result of the snowpack insulating the surface.

### 4. Rapid Temperature Drop from Approximately Freezing to Near or Below Zero

A rapid plummet of the temperature in a relatively short period of time is necessary for a frost quake occurrence. The high temperature was already near or above freezing, between 30°F and 40°F, and the low temperature was typically near or below 5°F following the cold snap, between –15°F and 5°F. The average temperature decline was about 30–40 degrees from the highest to the lowest reported values. The case studies presented here show that these temperature drops ordinarily occurred on a timescale of 16–48 hours.

## Noisy Nuisances of Winter

Frost quakes are rare anomalies that have been receiving more interest since their numerous occurrences throughout the past couple of winter seasons. There are many variables that must co-exist for frost quakes to ensue. It is clear that meteorologists and atmospheric scientists alike can have the ability to forecast frost quake outbreaks with more documented case studies of such intriguing natural phenomena. W

*STEVEN M. BATTAGLIA received a B.S. in atmospheric science and geology from the University of Illinois at Urbana-Champaign. DAVID CHANGNON is a meteorology professor at Northern Illinois University.*